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HIGH ENERGY COMPUTED TOMOGRAPHIC INSPECTION OF MUNITIONS

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November 2016

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U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Enterprise and Systems Integration Center

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14. ABSTRACT
This work is presented to show the progress in equipment developments made over the last several years on a specialized computed tomography (CT) inspection system specifically built for the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ. This compilation provides brief overviews of the hardware design, some of the digital processing functions that are exclusive to the developer, and how this inspection is directly applied to inspecting munitions and weapon systems. In many cases, the use of CT is overlooked or discounted due to its lack of use in high throughput production settings because of the time it takes to acquire adequate data sets and reconstructions. This report will show the added benefits of using CT as a supplemental inspection on sampling, providing greater knowledge of what may be causing suspect indications during the assembly or manufacturing process, and achieving more accurate results when determining the cause of a product failure during testing. Although the acquisition and review of the data takes longer than standard two-dimensional radiographs in one or more planes, the increased probability of detection is significant enough to mean the difference between finding the cause of a defect/condition or not. It also can provide valuable feedback during the development and early manufacturing of an item by giving additional perspective on part placement, alignment, and location of specific criteria of the inspection piece that cannot otherwise be accomplished by other nondestructive testing methods.

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PREFACE

This is a technical overview showing the application of using advanced computed tomography (CT) for the inspection of munitions and weapon systems. Although CT cannot produce full rate production throughput, the quality assurance it can provide on research and development components, reverse engineering, and malfunction investigations is unmatched. Using CT within the Department of Defense is highly beneficial to ensure the end products function correctly and are effective.

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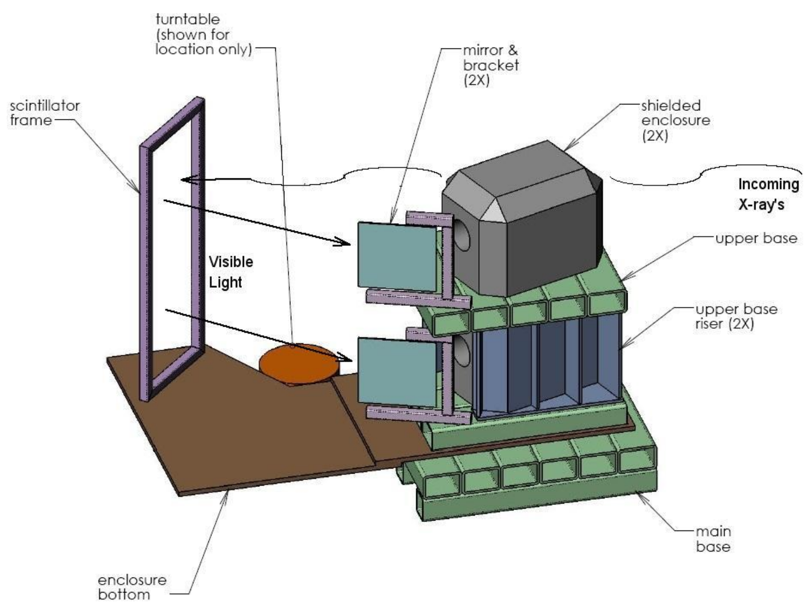
Jim Youngberg: Physicist/Computer scientist, Midvale, UT - main equipment designer and developer, president of JDLL Inc.

Dave Argyle: Computer scientist, Midvale, UT - main equipment designer and developer, JDLL Inc.

SYSTEM BACKGROUND

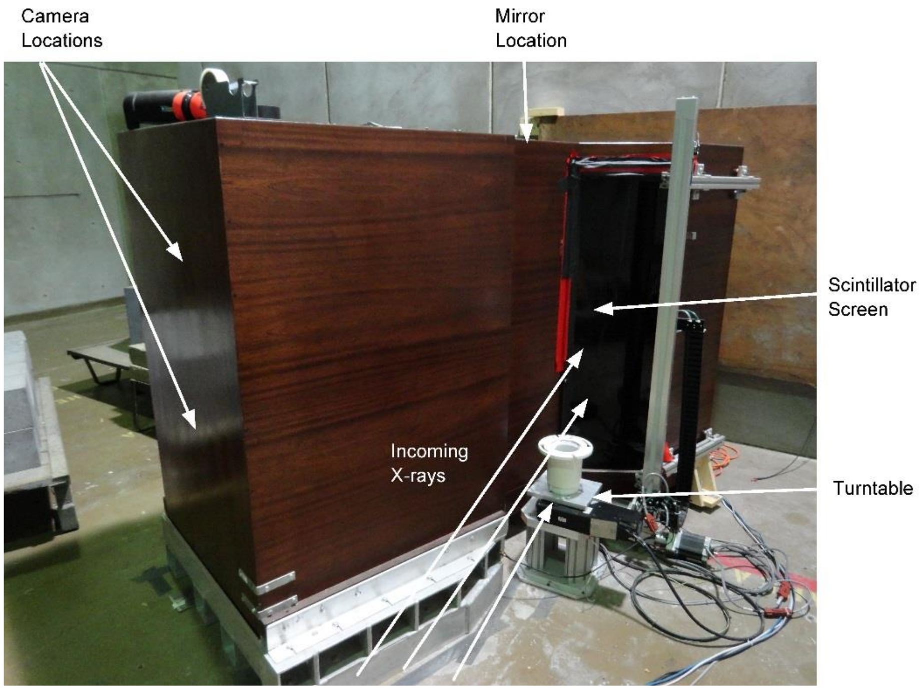
An advance computed tomography (CT) system was recently built by JDLL Inc., Midvale, UT, and delivered to the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, for the inspection of munitions. JDLL is a small business that has built several radiographic systems for the Joint Services for over the last 15 years. Their work includes CT systems used for the inspection of penetrator rounds and the design, development, and construction of automated body armor inspection systems (ref. 1). The system examined within this report is a charged coupled device (CCD) camera based CT system designated with the name “eXperimental Imaging Media” (XIM). The design incorporated shielding for use up to 4MeV x-ray photons and integrated two separate cameras into one single field of view (FOV). Other major distinguishing characteristics include its processing functions to digitally piece the two cameras together, use of advanced artifact reduction principles, performing reconstruction simultaneously during acquisition, and its development in accurate beam hardening corrections through digital means (ref. 2).

The overall setup of the system is shown in figure 1 and depicts the internal layout of the cameras, shielding, scintillation screen, and rotational fixture. The general layout is comparative to a common 16-bit CCD camera radiographic imaging system. The x-ray photons pass through the inspection piece and impinge onto a scintillation/phosphor screen where the energy is converted into visible light. From there, the light is redirected off a series of mirrors that allow the cameras to be out of the direct line of sight of the main radiation beam. The light is then focused through the camera lens and into a cooled CCD chip. At this point, the information is converted and digitized into a radiographic image. This process is repeated for multiple planes/projections as the part is rotated, acquired, and rotated again until enough information is obtained to achieve a volumetric file with a specified resolution. Figure 1a is the internal drawing of the XIM (ref. 2), figure 1b is a photograph of the layout of the XIM CT system built by JDLL Inc., and figure 1c is a photograph of the shielded camera housing inside the XIM CT system.



(a)

Figure 1
Overall setup of the system



(b)

(c)

Figure 1
(continued)

The radiation source matched with the XIM is a Varian M3A dual energy linear accelerator (LINAC) with a 1.2MeV and 3MeV setting. For the purposes of this report, all of the imaging was performed at 3MeV. This was mainly a result of a lower dose rate produced by the accelerator, a loss in conversion efficiency, lower phosphorescence of the conversion screen, and an overall reduction in the signal received by the cameras at 1.2MeV. This issue could have been adjusted for by reducing the source to detector distance (SDD), but to sustain consistent spatial relationships, a fixed SDD was used. The overall techniques used within this discussion were performed using 360-deg rotation, a SDD of 162.4 in. (4.1 m), a fixed spot size of roughly 2 mm in diameter, and a source

to object distance of 152.7 in. (3.9 m). The useable FOV, collimation, exposure/pulse settings, and the positioning of the inspection piece in relation to the floor were optimized as needed in relation to the part under investigation. The achieved spatial resolution ranged from 0.033 in. (0.883 mm) to 0.011 in. (0.279 mm). The number of pixels for each camera was more than 4008 length by 2672 width. The limitation on the resolution was primarily a factor of the final file size of the volume reconstruction and not a general limitation of the imaging portion of the system. The images provided later in the results section were acquired with 540 to 720 projections and varied with the useable FOV to sustain a consistent volume size to prevent processing issues related to the use of a central processing unit based computer.

Unique Features

The design created by JDLL Inc., in collaboration with Skiametrics, Inc., Winchester, MA, provided an electronics package that can withstand radiation fields produced by a 3MeV LINAC. The location of the cameras, the angle of the conversion screen and mirrors, as well as the shielding thickness were all optimized to ensure the dose rates received by the camera and digitizing electronics were nondetrimental to the lifetime of the components. The main shielding consists of molded lead boxes specifically tailored to match the camera and lens size chosen for the system. The thickness of lead was greater than 1.5 in. (3.8 cm) thick surrounding each camera. The use of leaded glass is the standard choice for CCD based imaging systems and was in use with the XIM as well. However, the thickness that was necessary to shield the radiation levels [greater than 3.75 in. (9.5 cm) thick] created additional constraints. To determine the thickness of the glass, conditions that impacted the incident path of the light photons coming off of the mirrors had to be assessed. Areas, such as the amount of diffraction that occurred over the path through this size of an optical lens, had to be optimized without comprising the spatial relation of projection data. The overall shielding was created to not only sustain longevity under continuous use but to reduce the noise attributed by induced dark currents within the cameras and electronics caused by the ionizing radiation. The scintillating/phosphor conversion screen of choice was a MCI/Optonix Kodak Lanex type that produces a green emission wavelength. This conversion screen was chosen for its inherent high spatial resolution but was a limiting factor in the acquisition speed of the system. Due to its inherent low conversion efficiency, in comparison to other available screen types, the required exposure time per projection was approximately 6.7 sec during an open field exposure (refs. 3 and 4). Another feature of this system is its ability to acquire and reconstruct the dataset simultaneously using only one computer. Most available CT equipment in today's market can only acquire a dataset and then reconstruct afterwards using a separate workstation. This is how claims of fast reconstruction times occur that are not based on the actual time it takes to acquire the dataset. The overall acquisition times vary depending on the size of the FOV, the x-ray generator output, the type of detection media, the number of projections, the required resolution, and several other factors included in a satisfactory technique. However, typical timeframes for commercial equipment and for the XIM CT system are in the range of 40 to 60 min in length.

Scattering Estimating Device

In addition to the commonly used bad/nonfunctioning pixel correction, gain, and offset calibrations, the XIM has been designed with an additional feature to reduce CT artifacts due to scattered radiation. Reduction of scatter artifacts is important in itself, but failure to reduce scatter also greatly complicates efforts to correct beam hardening artifacts. This device was designated the scattering estimating device (SED). This device's objective is estimation and removal of radiation whose immediate origin is anything other than the accelerator target. Scatter is estimated anywhere on the imager by introducing an attenuator along the beam path leading from the accelerator beam spot to the point of measurement. The attenuator must effectively eliminate the primary beam while allowing scattered radiation from virtually every other direction to arrive at the point of measurement unaffected. Because a single-point attenuator is impractical, a bar-shaped lead or tungsten

attenuator is used in practice. This horizontally-oriented high density bar is then translated from the bottom of the FOV up through the top edge of the imager's conversion screen. The scatter so estimated can then be removed from a normal projection subtractively. Figure 2 shows the SED. This device was only used sparingly due to minor challenging hardware issues such as an undersized stepper motor for the weight of the bar and the underestimated malleability of lead to bend under its own weight when extended across the full length of the detector. The SED is a valuable tool in fully optimizing the image quality but was excluded in the acquired images provided in the results section.

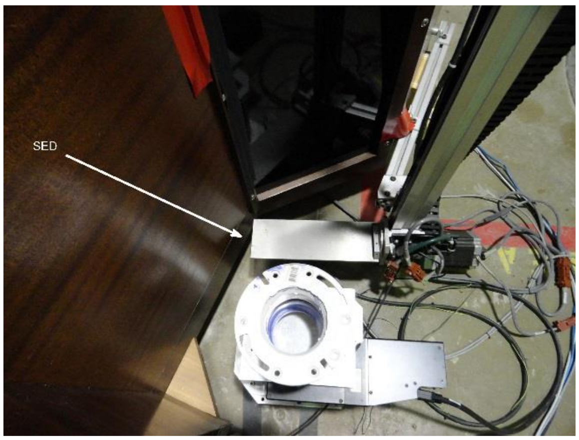
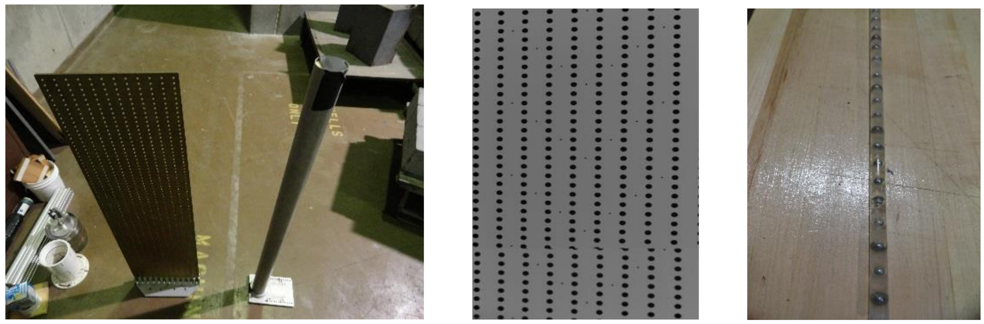


Figure 2
Photographs of the SED built into the XIM CT system

Distortion and Geometric Calibration Procedure

This system uses two imaging cameras and has a total FOV height of 3 ft. The geometric distortion introduced by each camera lens, which increases as the distance from the optical center of each image increases, is substantial and must be corrected in order to carry out accurate CT reconstruction. In addition, the spatial relationship of the individual pixels in the two images must be known.

To solve these specific issues, JDLL designed and built a hole phantom that contains a pattern of known-position holes to assist in the correction (ref. 2). The process of this correction entails both cameras imaging the hole phantom. Using the known position of the holes, the distortion of each lens is corrected and the two corrected images are stitched into one image. This correction requires partial overlap between the two camera FOVs in order to assure the same row and column of holes match. Otherwise, the two views could be stitched together with the wrong row and column connected. An example of a failed distortion calibration is shown in figure 3 where the two stitched camera views are not correctly aligned both vertically and horizontally. This calibration must be performed whenever the geometric relationship of the two imagers and the conversions screen changes. Figure 3a shows a photograph of the distortion and geometric calibration phantoms, figure 3b shows an image showing an incorrect distortion calibration, and figure 3c shows an early miniature version of the geometric calibration ball phantom showing the internal ball bearings.



(a) (b) (c)

Figure 3
An example of a failed distortion calibration

Once the distortion calibration is completed, the relative positions of the beam spot, the rotation axis, and the imager are determined using the geometric calibration procedure (ref. 2). Geometric calibration must be performed whenever the relative positions of the beam spot, rotation axis, and imagers are changed. The procedure uses a vertical array of equally-spaced ball bearings that are placed on the rotation stage at a distance from the center that projects within the imagers' horizontal FOV. During rotation of the phantom, the center point of each ball bearing travels in a circular orbit about the axis of rotation of the turntable. The projection of each ball's orbit is used to infer the position of the center of its orbit. The collection of centers, measured from each ball bearing, provides a measure of the tilt of the axis of rotation relative to the imager. The more ball bearings that can be contained within the FOV during the calibration, the more center positions can be measured. In turn, the more positions that are measured, the more accurately the geometry can be estimated and, therefore, the more precise the back projection calculations will be during reconstruction.

Beam Hardening Calibration

Beam hardening is inherent in radiographic measurement using a polyenergetic (Bremsstrahlung) beam. It results from material attenuation that varies with photon energy. As a Bremsstrahlung beam passes through an object, its spectrum is changed as a function of the materials it traverses. This violates CT reconstruction's fundamental assumption that each infinitesimal volume in space attenuates the x-ray beam an amount independent of what else the beam has passed through. The resulting beam hardening artifacts occur in CT of both single-material objects and objects comprised of several materials, but the presence of multiple materials greatly complicates the correction problem. Beam hardening artifacts in CT include elevation of reconstructed values in homogeneous materials toward the edge of the material and emanation of false high density values along lines connecting true high density areas.

To correct beam hardening, it is necessary to take into account the material(s) and its distribution in the subject. In the case of a single material, a two-parameter approximate attenuation correction is feasible. For this case, the XIM provides an automatic algorithm to optimally pick these two parameters. This algorithm performs best when scatter has been minimized. The XIM also provides algorithms for reducing beam hardening artifacts in cases where two or more homogeneous materials are present. The number and nominal reconstructed values of included materials must be specified. These artifact reduction algorithms do best when scatter has been minimized in measured views and when rotational symmetries are present in the subject. In figure 4, two high density rods are shown to cause noticeable beam hardening artifacts. On the inner surface of the rods (closest to the center) it almost appears as a smearing effect, widening the region of where higher grayscale values (whiter) are registered beyond the actual rod.

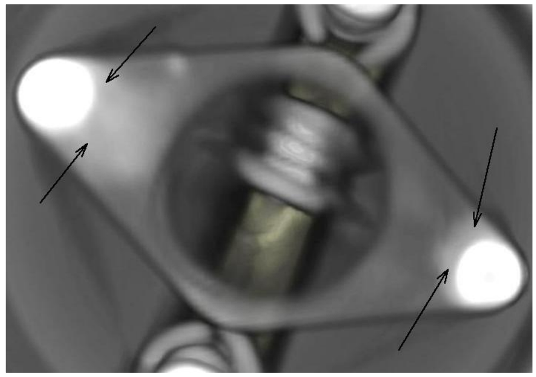


Figure 4
An example of the beam hardening artifact that surrounds two high density rods within a CT reconstruction

Figure 5 depicts what the user sees when performing a beam hardening calibration using the XIM CT system.

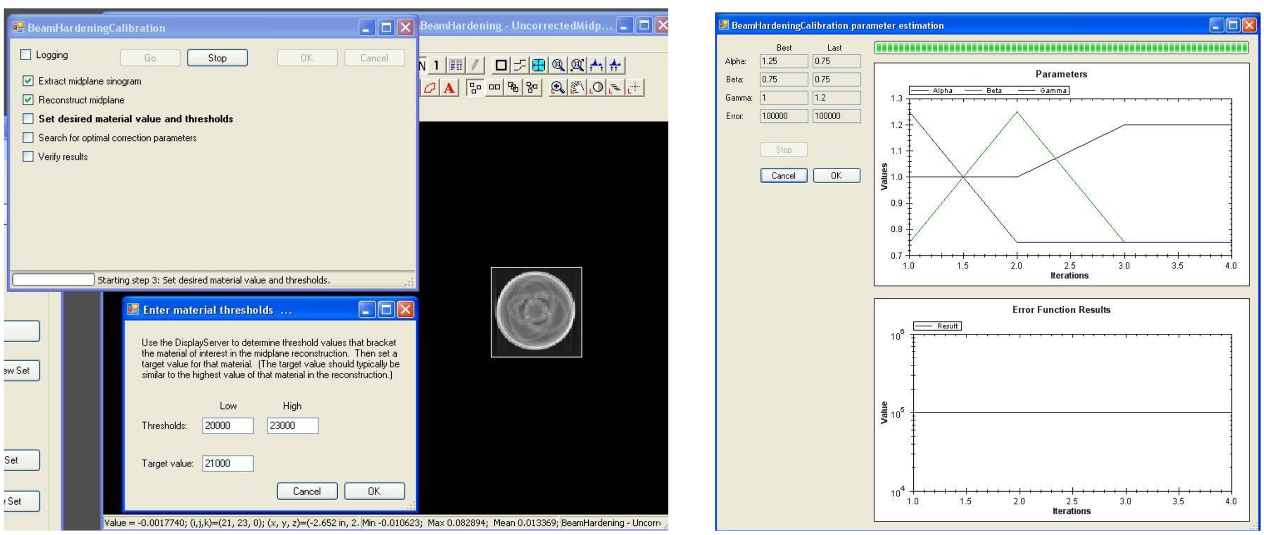


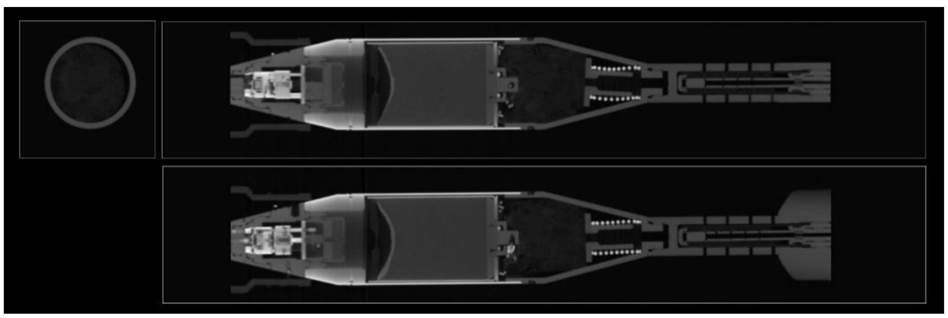
Figure 5
Graphical interface when performing the beam hardening correction and calibration

PRELIMINARY ACQUITIONS, RECONSTRUCTIONS, AND VOLUME RENDERINGS

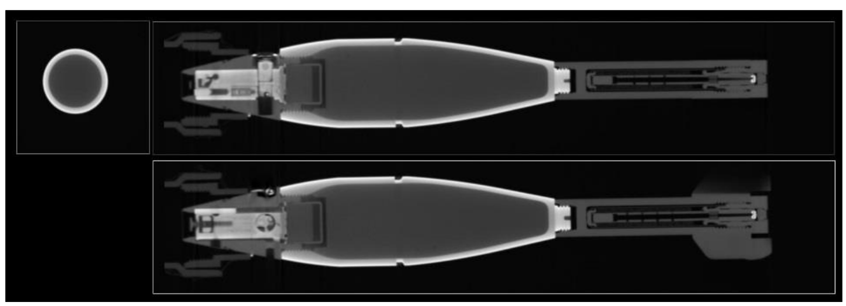
The XIM CT inspection system was primarily designed and tailored for thick and/or densely surrounded munitions including: tank, howitzer, paladin, area denial mortars, and shoulder launched projectiles and cartridges. Many of the larger (60 mm and greater) sized munitions within the U.S. Army and Joint Services use steel or other dense metal as the casing. The extreme forces that occur during the ignition and propagating stages of firing these munitions from their respective weapon system can create unsafe conditions if strong casings and exteriors were not used. In the manufacturing of these products, radiographic inspection is typically accomplished with only a one or two orthogonal plane techniques. This ensures assembling, casting, and/or handling did not cause any unwanted conditions internally that may affect the intended function of the product. In many cases, defense products are imaged prior to final assembly because of the complexity that is added

to the complete system. Full up assemblies can make any nondestructive testing inspection, including two dimension radiographic imaging, difficult or near impossible depending on design, materials, configuration, etc. This is where higher energy inspections are required, volumetric data is needed, and a high overall resolution must be maintained. Combined, these conditions are generally not applicable to many of the commercial off-the-shelf (COTS) CT systems available on the market.

Figures 6 and 7 provide a brief range of muntions that have been inspected by the XIM CT system with a high level of accuracy, with adequate image quality, and repetitive functioning. Figures 6 and 7 provide a perspective on the dynamic range and/or latitude that is achievable with this system. The illuminating cartridge (figs. 6a and 7a) has an aluminum outer casing, a relatively low density pyrotechnic, and very high density fuzing components. On the other hand, the high explosive (HE) version (figs. 6b and 7b) has a relatively thick steel casing and requires a high level of contrast sensitivity not typically achievable in higher energy inspections.



(a)



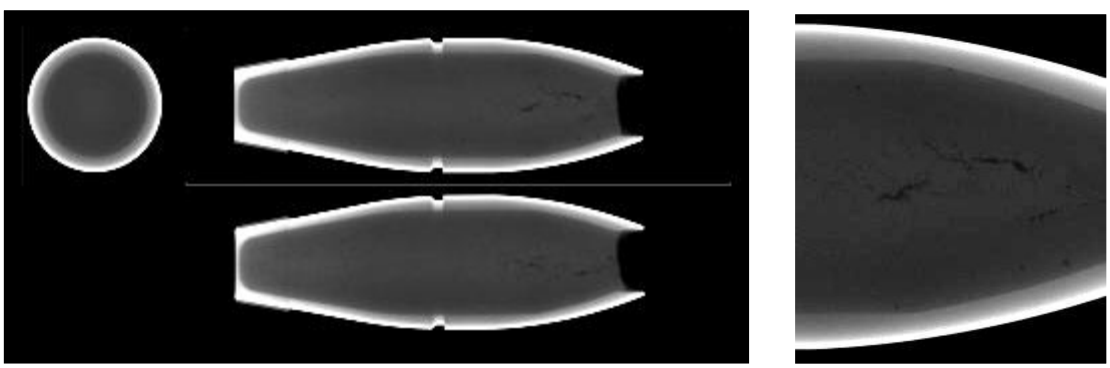
(b)

Figure 6
Volume reconstruction of a 60-mm projectile

(a) (b)

Figure 7
60-mm mortar cartridge volume rendering

In figures 8 and 9, additional representations are shown on the achievable image quality of the XIM CT system. These two inspection pieces have a very high linear attenuation and steel thickness equivalent (>2 in.), require a spatial resolution that is close to 0.01 in., and is consistent over a FOV that ranges from 6 in. to 3 ft in height and up to 1 ft in width. The inspection criteria for these types of munitions include the determination of base gaps or separations between the energetic material and the surrounding interface, areas with the conglomeration of cavities or pores, inclusions, proper assembly, and the safety conditions of the fuze (if present). Figure 8a is a volume reconstruction of a 120-mm mortar projectile, and figure 8b is a close-up of cavitations and voids within the energetic fill.



(a) (b)

Figure 8
Volume reconstruction of 120-mm mortar projectile

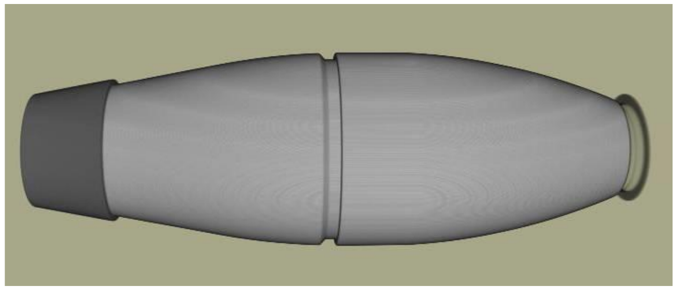
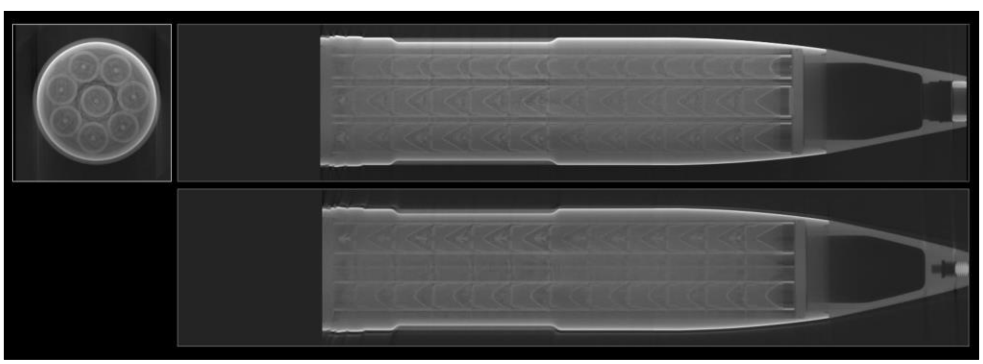


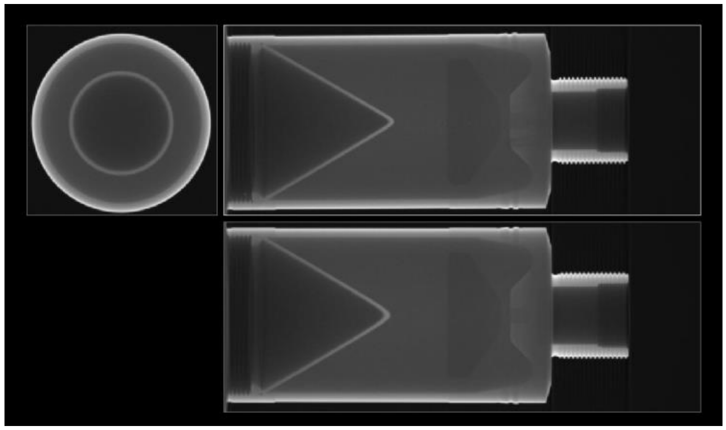
Figure 9
120-mm mortar projectile volume rendering

In other munition designs, electronic subassemblies for guidance and/or arming need to be inspected prior to testing or potentially after a malfunction has occurred. This particular CT system is capable of such inspections, but examples cannot be shown due to the sensitive nature of their mechanics. However, other examples that can show complex internal geometries are presented in figure 10. Both of these inspection pieces contain designs where standard two-dimensional imaging cannot determine the overall state of their internal components. The projectile assembly shown contains small sub-munitions, which would be an overlapped distorted image that is uninterruptable if taken two-dimensionally. Each row of these sub-munitions is independently placed in comparison to the adjacent row, and no single plane can be used for a clear unabated image of the sub-munitions. The shaped charge warhead shown in figure 10 requires complete coverage of the liner to determine if the explosive is fully intact with it. Separations between the two may cause an unwanted shape of the resulting liquid jet and, therefore, a potentially less effective penetrator. In the designs where copper or molybdenum are used, beam hardening artifacts are especially important to reduce. A high degree of assurance is needed to ensure the interface is actually one fully joined piece. Sufficient contrast sensitivity around the high and low density adjoining edges is necessary, and hardening artifacts can greatly reduce the quality of the inspection in that region, if not properly corrected.



(a)
155-mm projectile containing small shaped charged sub-munitions

Figure 10
Volume reconstruction of 155-mm projectile and 120-mm warhead

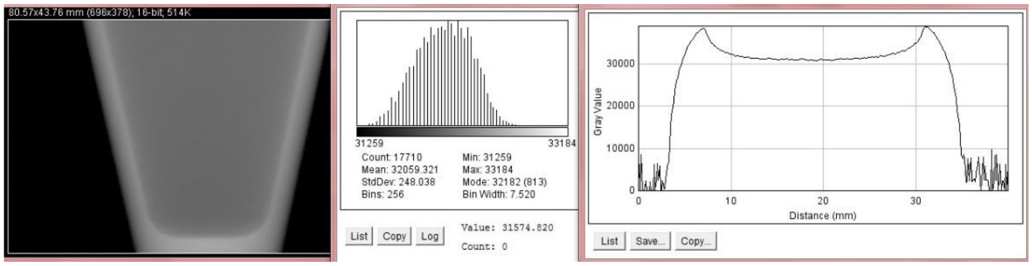


(b)
120-mm large caliber shaped charge warhead

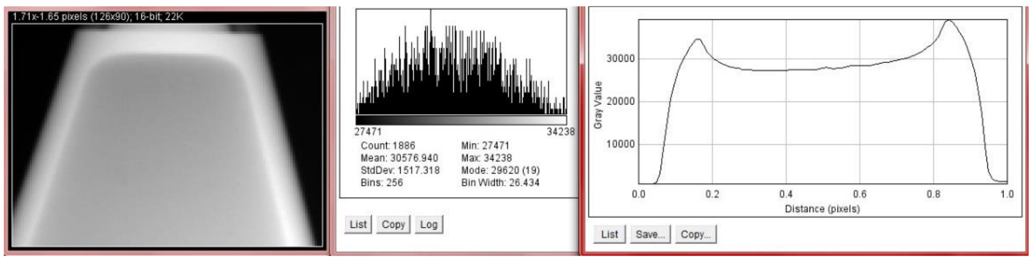
Figure 10
(continued)

Basic Image Quality Comparison

A very basic review of the image quality is provided in this section to show a baseline comparison to other single plane radiographic inspections. Figure 11a shows a representation of a two-dimensional projection taken previously on a separate detector. Figure 11b also portrays a sample image selected from the corrected XIM CT dataset for one of the HE cartridges provided in figure 6. Following each image, respectively, is an additional screenshot to show the graphical data of a histogram taken within the main area of interest in the lower half of the sample and a line profile across the center of the image as well (left to right). This general measurement is shown in the worst case area for noise closest to the thickest region of the steel casing where increased internal scatter is present. From the histograms and the mean grayscale values taken from a variety of different samples (not shown), a nominal signal to noise ratio (SNR) was measured/calculated to be approximately 180 in the single plane images. In the images taken with the XIM CT system, the histograms provided data that equates to a SNR of roughly 175. When comparing these SNR values with industry standards such as American Society for Testing and Materials E-2597, it can be interpreted that these images have a contrast sensitivity of approximately 1.5% (ref. 5). In addition to a respectable SNR/contrast sensitivity, the line profile for each example shows a consistent smooth response between the two interfaces of the exterior casing and the internal HE. This also shows that the image quality of the corrected dataset from the XIM is right in line and comparable to the image quality obtained in an inspection obtained with a COTS digital detector array (DDA) or flat panel digital radiography system. Additional discussions can be made in comparing inherent losses in measurements taken directly from the reconstruction rather than the corrected dataset, but that is outside of the scope of this general comparison.



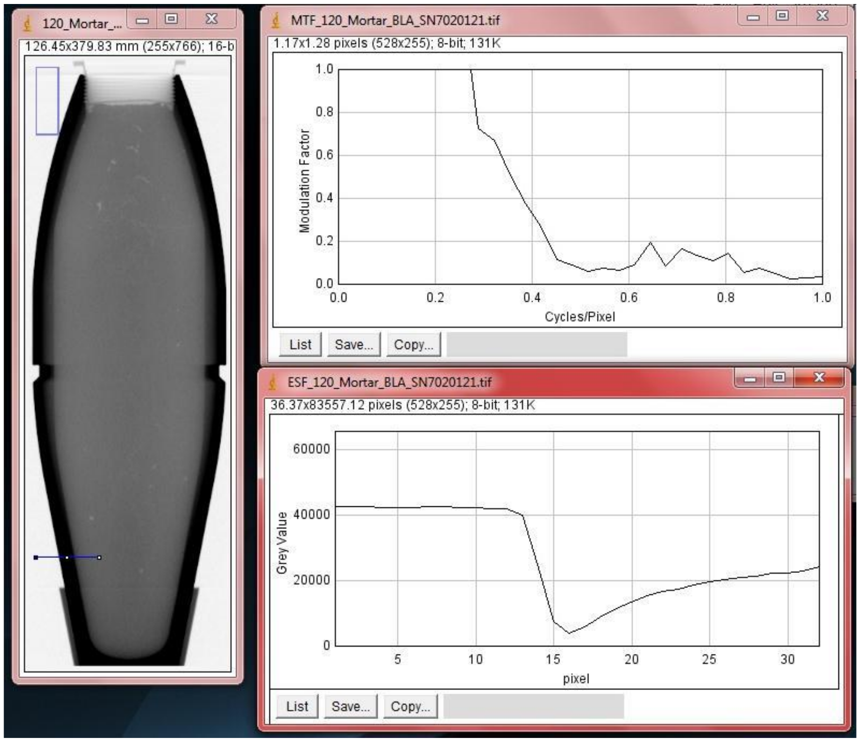
(a)
Raw image, histogram, and line profile across a standard single plane inspection of an HE mortar



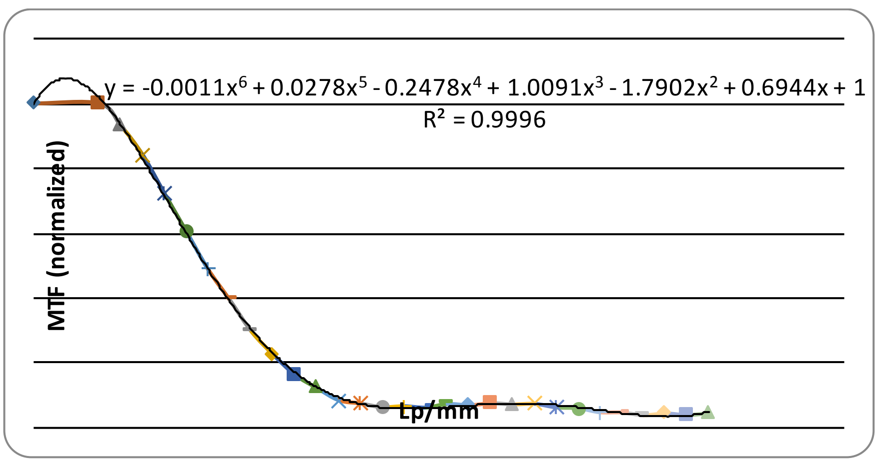
(b)
Raw image, histogram, and line profile across a single corrected reconstruction plane of an HE mortar imaged on the XIM

Figure 11
Raw image and graphical data of HE mortars

For an additional baseline comparison of the system's abilities, the modular transfer function (MTF) was measured. This was accomplished using the slanted edge plugin within the publicly available ImageJ software package (ref. 6). The measurement process and results are depicted within figure 12 and show the MTF versus cycles per pixel. This figure also shows the graph of that data, but with a normalized MTF versus the line pairs per millimeter (Lp/mm). The result of the 6th order polynomial trendline of the data provided an MTF at 50% to be approximately 1.27 Lp/mm and 2.2 Lp/mm at a MTF of 10%. These results show a comparable equivalent to the specifications for several other commonly available DDAs. Although this is a standardized method in comparing optical systems, the most valuable determination on a given system's ability is through using representative quality indicators (RQI). The use of RQIs or master standards with known or predesigned defective conditions are a definitive way to assure the technique, setup, and image quality meets the requirements of the inspection. This is the primary practice of image quality control that was used with the XIM.



(a)
Measurement of the MTF and edge spread function using ImageJ and the slanted edge plugin



(b)
Graphical layout of the normalized MTF versus the Lp/mm with a 6th order polynomial trend line

Figure 12
The measurement process and results of the MTF

CONCLUSIONS

Since the installation of the high energy “eXperimental Imaging Media” (XIM) computed tomography (CT) system at the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, a significant number of inspections have occurred. Investigations on large munitions, defense components, and weapon systems have taken place that were previously uninspected by volumetric radiographic inspection. The design, construction, and implementation of a high energy CT system has opened the door to the U.S. Army and Department of Defense (DoD) community for increased efficiency in developing new hardware designs and increasing the reliability of determining failures when they result in such systems. In addition, new advancements made in artifact reduction by the manufacturer and developer JDLL Inc. have turned this initial research and development project into a viable and practical technology that is applicable to both the defense and private sector nondestructive testing industry. Further refinements in the scatter estimation device hardware are needed to complete the full operational status of the XIM CT system as well as introducing variable collimation on the x-ray source. Overall, the achieved image quality is seen as a huge success considering the DoD has some of the most stringent inspection requirements and standards for quality control. There also remains a possible future exploration on transferring this methodology over from a cone beam reconstruction model into the newer helical reconstruction style, which may present an even larger innovation in CT inspection technology.

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High Energy Computed Tomographic Inspection of Munitions
Title

____
Project

Stephan Zuber
Author/Project Engineer

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Report number/Date received (to be completed by LCSD)

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